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ULTRAFILTRATION TO SUPPLY DRINKING WATER IN INTERNATIONAL DEVELOPMENT: A REVIEW OF OPPORTUNITIES

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Abstract

One of humanities biggest problems at present are millions of preventable deaths in developing countries. Most of those deaths are caused by microoganisms, often from sewage contaminated drinking water. Hence, technology to remove such contaminants is a first step to solving the problem. One such technology is ultrafiltration (UF). UF is a membrane filtration process in which water is pushed through a physical filter with a transmembrane pressure supplied by a pump or gravity. The pore size of such membranes is such that bacteria and most viruses can be effectively retained. As a consequence, this process has the ability to disinfect water physically and hence prevent water related disease and death from microorganisms. In this paper the performance of existing UF membranes and systems will be reviewed in terms of pathogen removal, water productivity (system capacity and flux), specific energy consumption per volume of water produced, which affect cost. Specific needs of systems to be installed and operated in developing countries as well as opportunities for the global community will be outlined.

Keywords: Ultrafiltration, developing countries, decentralised treatment, renewable energy, pathogen removal, water supply.

1 Introduction

Water related problems are increasing around the globe, with regard to both quantity and quality. In the current international Decade for Action ‘Water for Life’ (2005-2015) (UN 2006) and the United Nations Millennium Goals (UN 2005) policy makers, practitioners and researchers are searching for ways to address the problems of millions of water related deaths each year, most of which affect children (Gleick 2002). In developing countries water and sanitation infrastructure is still lacking which is the major cause for this problem. While technology has long been available, common obstacles are ‘lack of investment, lack of political will, and difficulty in maintaining services’ (Montgomery and Elimelech 2007). Many communities in developing countries are vastly lacking infrastructure such as water pipes, an electricity grid, or access to a knowledge base to design, build and maintain treatment facilities, this poses a significant

challenge. In now developed countries similar conditions prevailed prior to industrialisation and the construction of a sewer and water supply infrastructure, commonly referred to as public health engineering (Strang 2004). This infrastructure remains in service today, although not without problems and in many remote locations in developed countries (such as aboriginal communities in Central Australia, Islands in the Mediterranean, some rural areas in Europe) remain without access to safe drinking water and or rely on expensive water delivery by truck or boat.

A secondary problem after microbiological pollution is the presence of natural or man-made contaminants such as arsenic, selenium, uranium, fluoride, nitrate or boron, which often result in crippling health effects or death due to chronic exposure (Schwarzenbach *et al.* 2006). Those compounds require advanced treatment technologies for reliable continuous removal as opposed to conventional methods such as sand filtration.

In developed countries, micropollutants such as endocrine disrupting chemicals and pharmaceuticals have become a concern, often also due to sewage contamination of drinking water sources. This has resulted in a questioning of the suitability of existing infrastructure (Weber 2006) as all water is being treated to a very high drinking water standard and then used for many applications such as toilet flushing, cleaning, car washing, and irrigation which do not require such high standards. While it is clear that the debate on this topic is ongoing, it invites the opportunity to take a different approach in developing countries and, at least in remote locations, trial a decentralised approach. UF lends itself as a very suitable technology for such an approach and it is in this spirit the technology is reviewed with regards to performance and likely energy demands of such systems.

2 Ultrafiltration for provision of clean drinking water

2.1 Principle of ultrafiltration (UF)

Membrane systems achieve a physical disinfection of water by physically sieving the waterborne organisms that are larger than the smallest pore size. Any material that is smaller passes through the membrane with the clean water or permeate. Subsequently, disinfection can take place without the need for chemicals. The assessment of the pore size and their distribution within a membrane are very important in the microorganism removal potential of the membrane (Jacangelo *et al.* 1991). Because of the primary application of UF to retain macromolecules, the ‘pore size’ of a UF membrane is usually expressed as molecular weight cut-off (MWCO) in Dalton (Da; g/mol). This molecular weight cut of can be converted into an actual pore size, which is commonly used for membranes with larger pores and UF is in the range of 0.005 to 0.04 µm (von Gottberg and Persechino 2000). Therefore, viruses, which have a larger diameter (0.01-0.1 µm) can be retained, although smaller species may pass through the more open membranes. Bacteria are much larger than the pores (1-10 µm) and their retention is hence not a problem as long as the filter is intact. A comparison of UF membrane pore size with the size of bacteria, viruses, water molecules and ions is illustrated in Figure 1. An overview of some common microorganisms and their sizes is given in Table 1.

Membranes have been used in sanitation and sterilization processes due to their ability to perform this physical disinfection. While microfiltration (MF, pore size 0.1-0.45 µm) have been shown to retain small bacteria such as *Pseudomonas diminuta* (Waterhouse and Hall 1995), MF cannot usually retain viruses. However, the pore size classifications of those two membranes overlap somewhat and often depend on manufacturer preferences. In consequence, it is important to know the pore diameters of specific materials and apply a healthy level of caution when selecting a membrane.

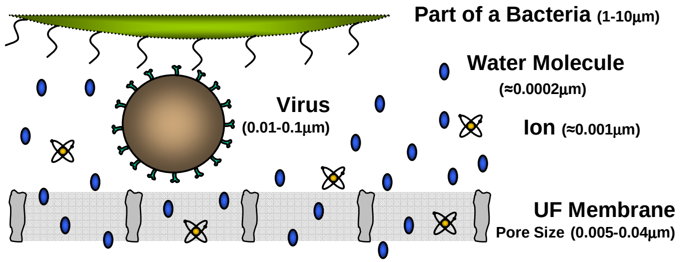

Figure 1 Comparison of ultrafiltration (UF) pore size and contaminant sizes (bacteria and viruses)

The transmembrane pressure, which is the driving force in UF, varies from -0.5 bar to about 3-4 bar. A negative pressure (suction pressure or vacuum) is applied in submerged systems, in which the membrane is immersed in a water tank and the product water then sucked through the membranes to the permeate side. This configuration is common in high solids applications such as membrane bioreactors for wastewater treatment (DiGiano *et al.* 2004) or high turbidity surface waters as the process allows simultaneous sedimentation of particles. In general, pressure increases as the pore size decreases due to the higher membrane resistance at a given productivity (flux). Flux is the permeate flow normalised per membrane area and ranges for UF from as low as 50 L/m^2.h to as high as 1000 L/m^2.h. While high fluxes reduce the cost of membranes due to the reduced need in membrane area, fouling and hence cleaning and maintenance costs tend to increase. Pilot trials with specific waters are recommended to determine realistic flux values and establish pre-treatment needs.

2.2 Ultrafiltration applications

UF is increasingly used to produce safe drinking water (Laîné *et al.* 2000), which can partially be attributed to increasing problems with microbiological contamination (in particular *giardia* and *cryptosporidium*). In fact, low pressure membrane processes such as UF and MF are capable of producing drinking water that falls in line with the standards set by the Surface Water Treatment Rule (SWTR) (Jacangelo *et al.* 1991). This combined with the decreasing costs of membranes (between 1994 and 2000 membrane costs fell by approximately 70%) has resulted in an increased adaptation of the technology (Laîné *et al.* 2000). However, in 2003, the majority of large scale plants are installed in the US (about 50%) while only 3 of 450 large scale (>400 m^3/d) applications are in Africa (Adham *et al.* 2005). It is evident that a significant market potential is yet to be satisfied. Less information is available on small scale systems and hence this paper aims at summarizing the most prominent small scale UF systems.

A number of other important applications of MF and UF are

(1) coupling with chemical additives such as coagulants or powdered activated carbon if smaller contaminants such as natural organic matter or micropollutants are to be removed;

(2) pre-treatment for nanofiltration (NF) and reverse osmosis (RO) to minimise fouling and prolong optimal operation conditions and membrane lifespan (Vedavyasan 2007). This is an important consideration for international development applications where long term operation of systems with minimal maintenance is important (Schäfer *et al.* 2007); and

(3) wastewater treatment and reuse, especially membrane bioreactors (MBR). Increased concern about contaminants in wastewater discharge and in some cases water recycling applications are driving such change combined with the advantage of a smaller footprint of membrane technology compared to conventional treatment. This area is a significant opportunity for international development for the control of wastewater and hence the contamination of water supplies (DiGiano *et al.* 2004).

2.3 Retention of pathogens (viruses and bacteria)

Removal of bacteria and viruses is describes as log removal (LR) which is defined in equation (1),

$$LR = -Log\left(\frac{n_{final}}{n_{initial}}\right) \qquad (1)$$

where n_{final} is the final virus count and $n_{initial}$ is the initial virus count. Given the varying shapes and sizes of bacteria and viruses (see Table 1), retention is often specific to the type of microorganisms provided its size is similar to the pore size. Tests are rarely performed with viruses and hence little data is available for specific species but common model viruses rather.

Microorganism removal with predominant 'conventional' water treatment technologies such as slow sand filtration or biological filtration is generally low and unreliable as virus retention in such filters is often dependent on the establishment of a biofilm. For example, sand filters achieved a 2 log removal (99%) for the MS-2 (0.028 µm) and 3 log (99.9%) for the PRD-1 (0.065 µm) bacteriophages (Yahya *et al.* 1993). The level of microorganisms must be reduced or inactivated to an extent so that they do not pose a treat to health when consumed and these results fall short of the guidelines set by the SWTR where, to be compliant, a 3 log removal or inactivation of *Giardia* needs to be achieved and a 4 log (99.99%) removal of viruses (Yahya *et al.* 1993).

The removal of viruses and bacteria from water supplies using low-pressure membranes has been well documented (Jacangelo 1995). Due to the nominal pore size of a UF membrane the majority of bacteria (>6 log) and viruses (>4 log) can be removed from a contaminated drinking water source.

Table 2 and Table 3 show the LR of viruses for a number of commercially available UF systems. Reported virus removal averages about 4 log (99.99%) in a reported range of 0.5 (MF) to 6 log with coagulation pre-treatment. Drouiche *et al.* (2001) have reported a 6 log removal of bacteria and a 4 log removal of viruses using small UF units. Given the size of bacteria, retention by an *intact* UF membrane is guaranteed.

However, viruses vary significantly in size and shape and in consequence validity of retention needs to be investigated with care. For example the the poliovirus, which is one of the smaller viruses, is spherical with a diameter of 25 nm (Andrews and Pereira 1964) which is smaller than a typical UF pore. There are hundreds of enteric viruses found in the faeces of humans and animals, each of them having very different shapes and sizes. Therefore any membrane that is investigated needs to be able to handle the range of viruses that are likely to occur in the water to be treated.

Given the difficulty of working with infectious viruses, phages (viruses that affect bacteria not humans) are widely used in membrane investigations to determine the efficiency of removal. Phages are organisms that are excreted by a certain proportion of the population (animal or human) at all times, and these individuals are non-infected, while viruses are excreted by

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infected individuals for a short period of time (Grabow *et al.* 1999). Coliphages are widely used as model viruses. They are easy to work with, give acceptable results and, most importantly, are non hazardous. Their size is also advantageous as it is very similar to pathogenic viruses (Otaki *et al.* 1998). For example, Herath *et al*. (1998) used RNA coliphages to replicate pathogenic viruses, their size and shape is very similar to that of pathogenic enteroviruses, along with four strains of *E-coli* phages, T4, QB, MS2 and fr. The T4 E-coli was used as it has a very irregular shape while the other three have icosahedron shapes, which is similar in shape to a sphere. *E-coli* is a thermophilic coliform which indicates faecal pollution from warm blooded animals (Ashbolt *et al.* 2001). Table 1 shows the size of micro-organisms used to model viruses.

	Microorganism Size (µm)		
Micro-organism	**Eq. Diameter**	**Length**	**Width**
Qß	0.025	-	-
MS2	0.025	-	-
Fr	0.019	-	-
T4	0.08	2.25	-
Psudomonas diminuta	1.05	2.68	0.56
Psudomonas putida	1.63	4.77	0.80
E-coli B	1.41	2.33	0.96
E-coli K12 A/λ	1.80	4.22	1.00
E-coli K12 C15	1.82	3.84	1.08
E-coli R	1.62	2.75	1.09
Alcaligenes Eutro (β)	1.00	1.34	0.79

Table 1 *Sizes of Micro organisms used to model viruses (adapted from (adapted from Herath et al. 1998).*

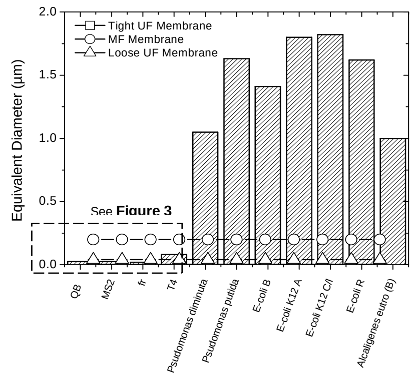

Figure 2 *Equivalent diameters of a number of micro organisms and typical membrane pore sizes, adapted from Herath et al. (1998).*

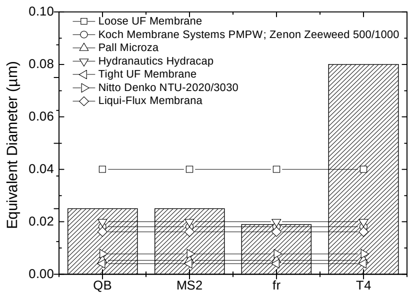

Figure 3 *Equivalent diameters of smaller micro-organism and the nominal pore sizes of a number of commercially available membranes.*

Looking at the sizes presented in Table 1 one can see that many microorganisms will not be challenging to remove. Removing the smaller viruses or phages effectively is more difficult, however. Figure 2 shows the difference in size between the sizes of selected micro-organisms and the pore sizes of typical UF and MF membranes. Organisms larger than the membrane cut-

off lines are retained. The area shown of specific interest in Figure 2 is the region where MF cannot remove viruses effectively (see Figure 3 for more detail). However, in this domain some UF membranes can successfully remove these viruses based on size exclusion.

In summary, based on bacteria and virus removal data available in the literature, UF is an ideal process to alleviate the problem of water related disease and death in developing countries, although further work to specifically investigate the retention of some common viruses in the field, system maintenance, membrane integrity and component failures would be beneficial.

3 UF systems in international development

Despite the obvious potential of UF to solve the problem of safe water in developing countries, to date very few such technology are making their way into the developing world on a long-term basis. UF systems are being used in humanitarian situations, an example being the donation of a number of small-scale UF/MF units for emergency disaster relief, such as the Sumatran Tsunami in 2004 (Zenon (2) 2005). During natural disasters damage is often caused to the sanitary infrastructure. Therefore, surface waters can become rapidly contaminated with faecal microbiota. If this water is to be used for drinking and is left untreated then an epidemic is likely to break out. As a result, UF can be used to remove these microorganisms to a suitable level and provide a sustainable alternative to bottled water. Unit operation in such disaster situations is generally short term and hence provides an opportunity for technologies that are not yet proven in terms of long term technical sustainability. Oxfam, for example, is seeking technologies for disaster relief that can operate for period of one year and that are 'disposable' meaning that they will not normally be recovered after a period of service (Bastable 2007).
Water supply systems sought for international development are typically 'low-tech'. Naturally, countries are poor, disposable incomes, if any, low and the lack of 'public health infrastructure' calls for the development of a sewerage and water distribution infrastructure as in the developed world. The required investment for such infrastructure is enormous and in consequence little progress is made. An alternative is to implement novel concepts such as decentralized UF systems, particularly in areas where distances from urban areas are large and infrastructure (water distribution systems and electricity grid installations) are expensive. This provides an area of potential investigation for the development of autonomous low-pressure membrane systems powered by renewable energies. To evaluate feasibility and potential costs it is of interest to review existing UF systems, their performance and energy consumption, in particular.

3.1 Existing ultrafiltration systems

Table 2 summarises a number of UF and MF system that are commercially available. Those systems are not necessarily suited to international development applications and most require existence of infrastructure such as an electricity grid. Some are designed for sewage rather than drinking water treatment. However, most of those systems can potentially be adapted into renewably powered systems for remote applications. A positive side-effect of the high quality water produced by UF is that any remaining viruses or regrowth of microorganisms in this water can be effectively controlled by disinfection processes as turbidity, which often interferes with disinfection processes, has been removed. This ultimately reduces costs of such post-treatment and the generation of a residual disinfectant concentration.

Table 2 *Table of selected commercial UF systems with published data (max. capacity, typical transmembrane pressure (TMP), log virus removal) andpublished/ calculated specific energy consumption (SEC) (based on operation at max. capacity).*

#	Company	System	Membrane	Max Capacity (m^3/h)	TMP (kPa)	SEC (Wh/m^3)†	Log Virus Removal	Reference
1	KMS	Konsolidator 78	Koch FEG Tubular Membrane	2.38	70	2333	4	(Koch Membrane Systems (1) 2004)
2	KMS	HF-4	Koch PMPW Hollow Fiber	13.3	240	410	4	(Koch Membrane Systems (2) 2005)
3	KMS	HF-6	Koch PMPW Hollow Fiber	25.4	240	615	4	(Koch Membrane Systems (2) 2005)
4	US Filter (Memcor)	EFC-400	-	5.5	-	-	-	(Siemens Water Technologies Corp 2007)
5	US Filter (Memcor)	EFC-424	-	11.0	-	-	-	(Siemens Water Technologies Corp 2007)
6	US Filter (Memcor)	EFC-1200	-	11.0	-	-	-	(Siemens Water Technologies Corp 2007)
7	Separation Dynamics	Extran Model "E"	Extran A2A	0.78	150	641	-	(Separation Dynamics)
8	Zenon	Z-Box-S, S6	ZeeWeed 1000	11.4	-	-	3.5	(Deakin 2007; Zenon (1))
9	Zenon	Homespring	-	2.52	-	-	5	(Deakin 2007; Zenon (1))
10	Pall Corporation	AP-1	Microza Hollow Fiber Membrane	7.0	250	214	4.5-6*	(Pall Corporation (1))
11	Pall Corporation	AP-2	Microza Hollow Fiber Membrane	12.0	250	855	4.5-6*	(Pall Corporation (1))
12	Pall Corporation	Septra	Septra CB	11.3	280	1197	4	(Pall Corporation (1); Pall Corporation (3))
13	Norit	Perfector	X-Flow Capfil Aquaflex	2.0	300	513	4	(Norit (1); Norit (2); Norit (3))
14	Gamma Filtration	Microlab 130S	Patterson Candy International (PCI-BX6) membrane	20.0	300	2308	-	(Drouiche *et al.* 2001)
15	Norit	Lineguard UF	X-Flow S-30	6.0	200	86	4	(Norit (4))
16	Solco	Skyhydrant	-	0.83	-	-	-	(Solco 2004)
17	Mono Pumps	WPS	Zenon	144.0	60	26	3	(Deakin 2007; Moore 2006)

†*reliable data for SEC determination is to date difficult to access and varies significantly depending on controls and operating parameters as well as assumption in estimation. This topic requires a more in depth analysis. For this reason data from* **Table 3** *for membranes only was used in this paper.*

* *based upon coagulation processes before filtration.*

3.2 Performance of membranes in terms of productivity and energy consumption

In order to determine power requirements of a UF system using a specific membrane needs to know the transmembrane pressure and feed flow. The power consumption P can be calculated as (Mulder 1996)

$$P = \frac{Q_F \Delta P}{\eta} \qquad (2)$$

Where Q_F is the volumetric feed flowrate (m^3/s), ΔP is the transmembrane pressure (N/m^2) and η is the pump efficiency (typically 0.5 - 0.8), giving a power value in Watts (Mulder 1996). The majority of the energy usage of such membranes systems is due to the applied transmembrane pressure, while monitoring and control equipment as well as fouling control also need to be

considered. Energy requirements of control systems have been neglected in calculations for the purpose of this paper.
The specific energy consumption (SEC) of a system is defined as the energy consumed in the production of a unit volume of water. This is based on the power consumption of the system, in this case simplified to the dominating unit which is the pump. SEC is defined as

$$SEC = \frac{IU}{Q} \qquad (3)$$

Where I is the current of the pump (A), U is the voltage (V) and Q is the permeate flowrate (m^3/h). However, since P = IU, power can be substituted into equation (3)

$$SEC = \frac{P}{Q} \qquad (4)$$

For calculation in this paper, flux data (if not published) was calculated using equation (5) with the maximum capacity of the membrane under question in order to give the maximum productivity of the system. This results inevitably in the minimum SEC value.

$$J = \frac{1}{A}\frac{dV}{dt} = \frac{Q}{A} \qquad (5)$$

When the membrane was classified with a MWCO it was converted to µm by using the Einstein-Stokes Equation. Einstein-Stokes Equation is defined in Equation 6, adapted from Worch (1993).

$$d = 4.074 \times 10^{-11} \cdot M^{0.53} \qquad (6)$$

where M is the molecular weight cut off expressed (Da, g/mol) and the d is the equivalent pore diametre (m). The Einstein-Stokes Equation assumes that the molecules are spherical and in consequence that pores are cylindrical.
Table 3 shows the performance of a number of commercially available membranes determined using the above relationships assuming maximum capacity operation and typical transmembrane pressure as published by manufacturers.
Figure 4 shows, as expected, that SEC decreases with increasing pore size and hence increased permeability. Flux data is somewhat misleading as it is determined by transmembrane pressure and hence does not increase with pore size as permeability.
Figure 5 shows log virus removal as a function of pore diameter. Based on the data collected in Table 3 and Table 4, it is evident that the performance of commercial membranes at full scale is lower than experimental studies. However, no clear distinction is visible between virus retention of MF and UF membranes. While MF membranes with pores >0.05 µm cannot remove more than 3 log viruses, results for UF arer scattered over a <2 log to >8 log range. This emphasises the need to perform tests for specific membranes and specific viruses to be removed.
One can further elucidate from the UF performance in Figure 4 and Figure 5 that higher virus removal is not necessarily resulting in a higher SEC as the more open UF membranes show a lower virus retention at higher SEC than the tighter UF membranes. This warrants further

investigation. Overall a substantial 4 log virus removal can be achieved with 'maximum capacity' SECs as low as 100 W.h/m^3, which is about 10-20 times lower than for a small scale brackish water desalination system using UF as pretreatment (Schäfer *et al.* 2007).

Table 3 *Table of commercially available membranes used in various systems (max. capacity, membrane area, TMP, Log removal) and published/calculated data (flux, pore diameter, SEC).*

#	Manufacturer	Name	Membrane	Max Capacity (m³/h)	Area (m²)	TMP (kPa)	Flux (L/m²h)	Pore Diameter (µm)	Log Virus Removal	SEC (Wh/m³)‡	Reference
1	KMS	PMPW	HF 8-48-35-PMPW	4.6	32.1	210	143	0.018 (MWCO 100kDa)	4	90	(Koch Membrane Systems (1) 2004)
2	KMS	PMPW	HF 8-72-35-PMPW	7.3	50.5	210	145	0.018	4	90	(Koch Membrane Systems (1) 2004)
3	KMS	PMPW	HF 10-72-35-PMPW	11.6	80.9	240	143	0.018	4	103	(Koch Membrane Systems (1) 2004)
4	KMS	PMPW	HF 10-48-35-PMPW	7.4	51.5	240	144	0.018	4	103	(Koch Membrane Systems (1) 2004)
5	Pall Corp.	Microza	OLT-3206	3.5	10.7	300	327	0.005	3	128	(Pall Corporation (1); Pall Corporation (2))
6	Pall Corp.	Microza	OLT-5026	3.5	23	300	152	0.005	3	128	(Pall Corporation (1); Pall Corporation (2))
7	Pall Corp.	Microza	OLT-5026G	7.5	23	300	326	0.005	3	128	(Pall Corporation (1))
8	Pall Corp.	Microza	OLT-6036	16	34	300	471	0.004	3	128	(Pall Corporation (1); Pall Corporation (2))
9	Pall Corp.	Microza	LGV-3010	-	-	-	-	0.006	4	-	(Pall Corporation (4))
10	Pall Corp.	Microza	LGV-5210	-	-	-	-	0.006	4	-	(Pall Corporation (4))
11	Pall Corp.	Septra	-	11.3	13.9	280	813	0.02	4	-	(Pall Corporation (1); Pall Corporation (3))
12	Hydranautics	Hydracap	40"	4.6	30	152	100	0.02	4	65	(Hydranautics)
13	Hydranautics	Hydracap	60"	6.8	46	152	148	0.10	4	65	(Hydranautics)
14	Inge	Dizzer 3000	-	3	30	80	100	0.05	-	34	(Inge)
15	Inge	Dizzer 5000	-	5	50	80	100	0.037	-	34	(Inge)
16	Liqui-flux	Membrana	-	4.8	61	70	120	0.016	-	-	Liqui-flux
17	Zenon	Zeeweed	500	1.8*	41*	200	51	0.035	2	-	(Deakin 2007; Zenon (1))
18	Zenon	Zeeweed	1000	3.6*	56*	200	65-85	0.018	3.5	-	(Deakin 2007; Zenon (1))
19	Norit	Aquaflex	S-225 FSFC PVC	17.3	35	400	494	0.026	4	171	(Norit (2); Norit (3))
20	Norit	Xiga	-	3.5	35	400	100	0.026	4	171	(Norit (4))
21	Norit	X-Flow	S30	4.7	6.2	300	758	0.026	4	128	(Norit (4))
22	USFilter	-	-	-	-	-	110	0.10	0.5	-	(Siemens Water Technologies Corp 2007)
23	USFilter	-	-	-	-	-	85	0.10	0.5	-	(Siemens Water Technologies Corp 2007)
24	Nitto Denko	NTU-3306-K6R	-	15	30	300	500	0.004	-	128	(Nitto Denko)
25	Nitto Denko	NTU-3306-K4R	-	7	14	300	500	0.004	-	128	(Nitto Denko)

‡ *SEC calculations are based on published typical performance data which is likely to deviate from real performance. It is essential that more data on power consumption be made available to assess the actual performance of such membranes.*

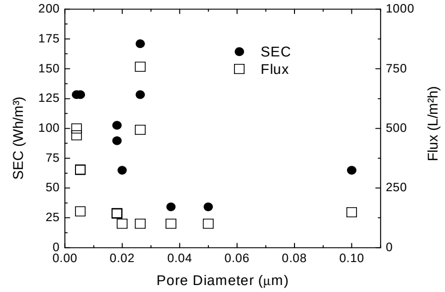

Figure 4 *Specific energy consumption and flux versus pore diameter (from* Table 3*).*

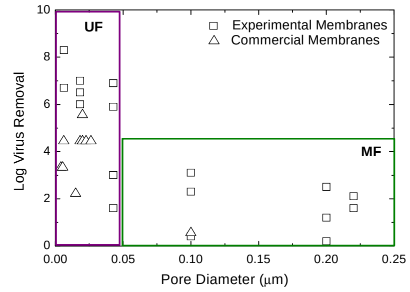

Figure 5 *Log virus removal as a function of membrane pore diameter (commercial (see* Table 3*) and experimental studies (see* Table 4*)).*

Table 4 *Experimental investigations of membrane performance. Adapted from (Ueda 2001)*

Membrane Type	Pore Diameter (µm)	Micro Organisms Removed	Log Removal	Reference
MF	0.22	Poliovirus	1.6	(Madaeni *et al.* 1995)
MF	0.22	Poliovirus	2.1	(Madaeni *et al.* 1995)
MF	0.2	Coliphage MS2	0.2-1.2	(Jacangelo 1995)
MF	0.2	Coliphage MS2	0.2-2.5	(Jacangelo 1995)
MF	0.1	Coliphage Qβ	2.3	(Urase *et al.* 1993)
MF	0.1	Coliphage Qβ	3.1	(Urase *et al.* 1993)
MF	0.1	Coliphage MS2	0.4	(Jacangelo 1995)
UF	0.043	Coliphage MS2	1.6-6.9	(Jacangelo 1995)
UF	0.043	Coliphage MS2	3.0-5.9	(Jacangelo 1995)
UF	0.018	Coliphage MS2	6.0-7.0	(Jacangelo 1995)
UF	0.018	Coliphage Qβ	6.5	(Jacangelo 1995)
UF	0.006	Coliphage MS2	8.3	(Otaki *et al.* 1998)
UF	0.006	Poliovirus	6.7	(Otaki *et al.* 1998)

3.3 Comparison of specific energy consumption with desalination systems

Since UF is a low pressure process (typically 1.0 – 5 bar), the required energy is significantly lower than that in nanofiltration and reverse osmosis units that operate in the range 5 – 20 bar and 10 - 100 bar, respectively (Mulder 1996). UF is ideal for the treatment of surface waters, while NF or RO are required if salinity or trace contaminants are of concern.

Schäfer and Richards have designed an autonomous desalination system that uses UF as a pretreatment step (Richards and Schäfer 2002, 2003; Schäfer *et al.* 2005, 2007; Schäfer *et al.* 2001; Schäfer and Richards 2005) driven by renewable energy for use in remote areas. There are a number of systems, which have coupled renewable energy, such as photovoltaics and wind power, in desalination applications to varying degrees of success. The performances of these systems with regards to specific energy consumption (SEC) vary significantly ranging from 1-2 kWh/m^3 (Schäfer *et al.* 2007) to 26 kWh/m^3 (Joyce *et al.* 2001). Since NF/RO operates at far higher pressure than UF, the SEC of UF would naturally be significantly lower. As result UF has a huge potential to be used cost effectively as a decentralised system in remote communities and in international development.

4 Conclusions

The review in this paper confirms that UF is a very appropriate choice for resolving the issue of lack of access to safe drinking water in developing countries as well as in disaster relief. The nature of this process in that it is reliable, simple, and energy efficient, makes it suitable for small decentralised systems. The energy requirements can be met in various ways using grid power (where available), renewable resources, generators, handpumps or sometimes gravity. If desalination is required such a system provides an excellent pre-treatment and acts as a double barrier for micro-organisms.

The implementation and maintenance of such systems and their technical sustainability remains to be dealt with. A possible approach would be for some companies focusing investment on selected countries in which, with the aid of donors or aid agencies, many similar systems are installed. With a large number of systems in certain areas it becomes workable to have maintenance personnel based in the area which then can assist with training local operators and offering initiatives such as a 'mobile membrane cleaning' service.

> *We are the first generation that can look extreme and stupid poverty in the eye, look across the water to Africa and elsewhere and say this and mean it: we have the cash, we have the drugs, we have the science - but do we have the will? Do we have the will to make poverty history?* (Bono, 2005)

We indeed have the technology and we have the knowledge to solve water problems in developing countries.

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